



## **Anisotropic superconductivity in NbSe<sub>2</sub> probed by magnetic penetration depth**

Pascale Diener, Pierre Rodiere, John D Fletcher, Anthony Carrington, Jean-Pascal Brison, Ruslan Prozorov, T. Olheise, Rw Giannetta

### **► To cite this version:**

Pascale Diener, Pierre Rodiere, John D Fletcher, Anthony Carrington, Jean-Pascal Brison, et al.. Anisotropic superconductivity in NbSe<sub>2</sub> probed by magnetic penetration depth. 8th International Conference on Materials and Mechanisms of Superconductivity and High Temperature Superconductors, Jul 2006, Dresden, Germany. pp.700, 10.1016/j.physc.2007.03.145 . hal-00965453

**HAL Id: hal-00965453**

**<https://hal.science/hal-00965453>**

Submitted on 25 Mar 2014

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Anisotropic superconductivity in NbSe<sub>2</sub> probed by magnetic penetration depth

P. Diener<sup>a</sup> P. Rodière<sup>a</sup> J.D. Fletcher<sup>b</sup> A. Carrington<sup>b</sup> J.P. Brison<sup>a</sup> R. Prozorov<sup>c</sup>  
T. Olheiser<sup>d</sup> R.W. Giannetta<sup>d</sup>

<sup>a</sup>CNRS CRTBT, BP 166, 38042 Grenoble Cedex 9, France

<sup>b</sup>H.H. Wills Laboratory, University of Bristol, Tyndall Avenue, BS8 1TL, United Kingdom

<sup>c</sup>Department of Physics and Astronomy, Ames Laboratory, Iowa State University, Ames Iowa 50011

<sup>d</sup>Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green St., Urbana 61801 Illinois

---

## Abstract

NbSe<sub>2</sub> shows coexistence of a charge density wave ( $T_{CDW} \sim 32\text{K}$ ) with a superconducting state below  $T=7.2\text{K}$ . Recent ARPES measurements revealed different values of the superconducting gap on the main sheets of the Fermi Surface. These results suggest a multigap superconductivity such as in MgB<sub>2</sub>. The temperature dependence of the magnetic penetration depth ( $\lambda(T)$  down to  $T_c/16$ ) has been measured on high quality single crystals in the Meissner state. A strong increase of the in-plane penetration depth is observed, signaling the presence of low lying excitations. Given the relative contributions of each Fermi surface sheet, these measurements indicate that a reduced gap is not necessarily only found on the small Se sheet as suggested by the ARPES measurements. These results are discussed in a framework of multigap superconductivity.

*Key words:* NbSe<sub>2</sub>, penetration depth, superfluid density  
*PACS:*

---

The hexagonal dichalcogenides NbSe<sub>2</sub> has attracted a large interest in the last few decades for the coexistence of an incommensurate charge density wave with a superconducting state below  $T_c=7.1\text{K}$  [1]. Furthermore, the superconducting state shows unusual properties, which can not be explained by an isotropic BCS weak coupling model. For example, the electronic specific heat has already shown the presence of a reduced energy gap [2]. Recently, NbSe<sub>2</sub> has been revisited in the light of multigap superconductivity. ARPES measurement suggested that the low energy excitation gap is due to the Se p-band which has a small electron-phonon coupling constant [3]. A directional probe combined to the particular anisotropy of the Fermi Surface of NbSe<sub>2</sub> allows us to test the excitation gap on the different sheets.

In this paper, we present high sensitivity measurements of the change of the in plane and c-axis temperature dependence of the magnetic penetration depth in the Meissner state (respectively  $\Delta\lambda_a$  and  $\Delta\lambda_c$ ). The detailed results are published elsewhere [4].

## 1. Experimental method

$\Delta\lambda_i$  (i=a or c) was measured with a LC circuit driven by a tunnel diode operating at 14MHz. The very low AC field probe ( $\sim 10\mu\text{T}$ ) and the screening of any DC magnetic field ensured that the sample was kept in the Meissner state. The frequency shift of the LC oscillator is directly proportional to  $\Delta\lambda$ .

Single crystals from three sources (Lausanne,

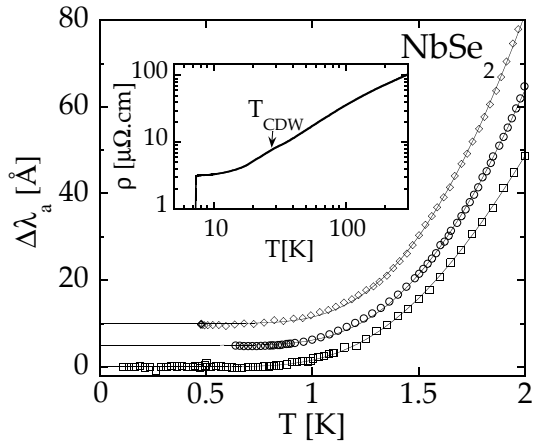


Fig. 1. Temperature dependence of the in-plane penetration depth for samples from different sources (measured at Bristol  $\square$ , Grenoble  $\circ$ , Urbana  $\diamond$ ). The field configuration is  $H\parallel c$  for Bristol's samples with an aspect ratio of 40. The contribution from the c-axis is negligible. For the other sample  $H$  is perpendicular to the c-axis. For clarity the data are offset. The lines are a fit with a superconducting gap of  $\Delta = 1.1 \pm kT_c$ . Inset, temperature dependence of the in plane resistivity for a single crystal from the same batch as Grenoble's samples.

Tsukuba, Bell Lab) have been measured in three different laboratories (Grenoble, Bristol, Urbana Champaign respectively). Crystals of thickness  $t$  were grown with large flat layers perpendicular to the c-axis. Each side of the samples were cut. Samples from different batches have a RRR between 33 and 70 (see inset fig. 1). No drastic change with sample quality has been observed.

When the magnetic field is applied along the c-axis, the supercurrents are flowing only in the basal plane. However, for a magnetic field applied perpendicular to the basal plane, both, a and c-axis directions are probed. For a sample of rectangular shape with a section ( $\perp H$ ) of width  $w$  and thickness  $t$ , the frequency shift is proportional to  $\Delta\lambda_a + \frac{t}{w}\Delta\lambda_c$ . To extract the out-of plane penetration depth the aspect ratio of a sample is changed by cutting.

## 2. Results

In fig. 1 the low temperature dependence of the in-plane penetration depth is shown. All the curves are fitted with the approximated expression (valid for  $kT < T_c/3$ ):

$$\Delta\lambda_i(T) \simeq \lambda_i(0) \sqrt{\frac{\pi\Delta_0}{2T}} \exp\left(-\frac{\Delta_0}{T}\right) \quad (1)$$

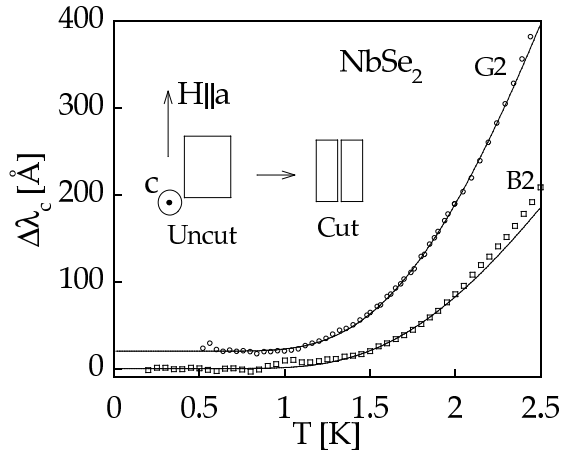


Fig. 2. Temperature dependence of the out-plane penetration depth calculated from a change of the aspect ratio (see text) (B2 measured at Bristol, G2 data from Grenoble is offset).

where  $\Delta_0$  is the superconducting gap at  $T = 0K$ . We find  $\Delta_0 = 1.1 \pm 0.1kT_c$ , less than the value expected for a weak coupling BCS gap ( $\sim 1.76kT_c$ ). In fig. 2 the low temperature dependence of the c-axis penetration depth is fitted for  $T < 2K$  with the same expression. A gap of  $\Delta_0 = 1.3 \pm 0.1kT_c$  is measured.

The experimental results have to be compared with the calculated Fermi surface. The Fermi surface of  $NbSe_2$  is formed of 2 cylinders along the c-axis from the 4d-electrons of the Nb and also a small flat pancake around the center of the Brillouin zone from the p-electron of the Se. This sheet contributes only to 2% to the total in-plane superfluidity but 85% to the out-plane superfluidity [5]. So the reduced energy gap measured by in-plane penetration depth is on one or more of the quasi-2D Nb sheets. Moreover,  $\Delta\lambda_c$  shows that the superconducting gap associated to the Se sheet is not smaller than the smallest gap of the quasi-2D Nb band. These results are in strong contrast with previous measurements [3].

## References

- [1] D.E. Moncton, J.D. Axe, F.J. DiSalvo, Phys. Rev. Lett. **34** 734 (1975).
- [2] P. Garoche, J.J. Veyssié, P. Manuel, P. Molinié; Solid State Comm. **19** 455 (1976).
- [3] T. Yokoya, et al., Science **294** 2518 (2001).
- [4] J.D. Fletcher, A. Carrington, P. Diener et al; Cond-Mat 0605059.
- [5] M.D. Johannes, I.I. Mazin, C.A. Howells; Cond-Mat 0510390.